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HYDROGEN-INDUCED STRESS CORROSION CRACKING SUSCEPTIBILITY ANALYSIS OF PITCH LINKS FROM THE AH-64 APACHE HELICOPTER

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ABSTRACT

AH-64 Apache helicopter pitch links were evaluated for degradation of mechanical properties due to service and susceptibility to hydrogen embrittlement. The pitch links were manufactured from 4340 electroslag remelted steel and heat treated to an HRC 52 hardness level and/or retempered to a HRC 38 hardness level and vacuum cadmium coated. Samples from fielded pitch links and virgin material were evaluated for comparison of mechanical behavior. Static torque-load tests on pitch links immersed in 3.5% NaCl at a potential of -1.2 $V_{(SCE)}$ were conducted for 1000 hours. Stress corrosion cracking resistance under hydrogen embrittlement conditions were determined.

Mechanical and stress corrosion testing demonstrated no discernable change in properties due to service. Retempering the HRC 52 pitch links to HRC 38 resulted in properties similar to those expected from the 4340 ESR steel directly heat treated to the same hardness level. The immersion tests indicated no failure of the pitch links even at six times the service torque. The retempered material exhibited greater resistance to hydrogen-induced cracking.

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INTRODUCTION

The pitch links for the AH-64 Apache helicopter control the attitude of the main rotor blades. They are flight-critical components because severe damage or failure of the components would lead to uncontrollable descent of the aircraft. A 4340 electroslag remelted (ESR) steel heat treated to a hardness of HRC 52 is used to manufacture the components. To avoid corrosion a vacuum-cadmium coating is applied. The pitch links are shown installed on the helicopter in Figure 1 with an enlargement of all the major components in Figure 2. Adjustment of the pitch links is achieved by rotating the central barrel which has a left-hand thread at one end and a right-hand thread at the opposite end; this varies the distance between the two oppositely threaded links containing the spherical bearings. A locating pin between the two links ensures they do not rotate relative to one another and the locking nuts ensure the barrel does not move. Torquing of the nuts imposes a tensile stress on the threaded region of each of the pitch links.

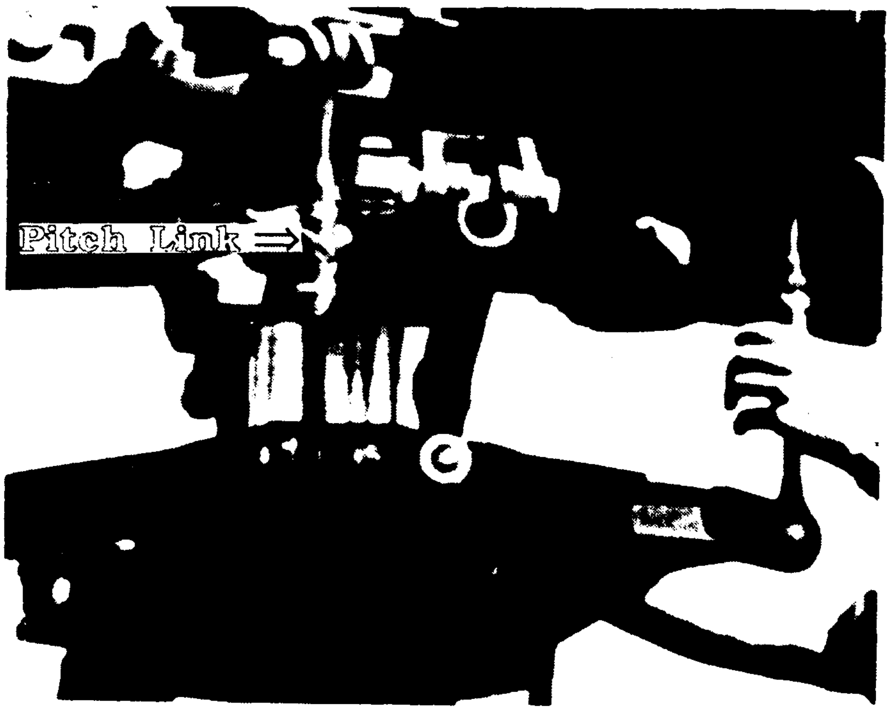


Figure 1. Photograph of the AH-64 rotor-blade area with the pitch link location highlighted.

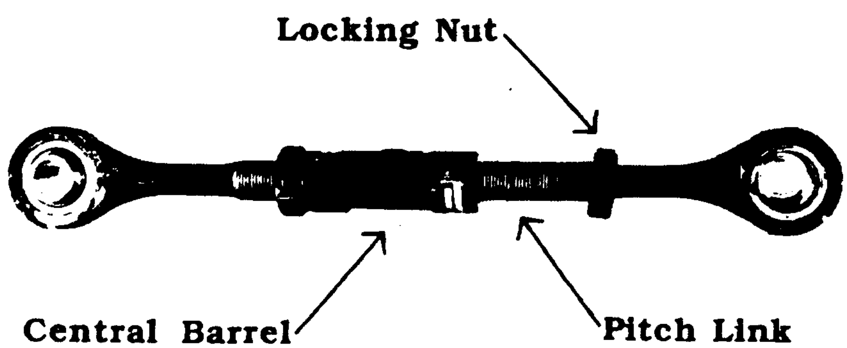


Figure 2. Detail of pitch link showing main components.

Since the components were approaching their design life of 1440 flight hours, the U.S. Army Materials Technology Laboratory (MTL) was asked by the U.S. Army Aviation Systems Command (AVSCOM) to assess a proposal to extend the pitch links' service life. This involved determination of the effect of service on the residual mechanical properties of the current material. Failure to extend the design life would have resulted in significant procurement costs and down time in order to replace the aged pitch links.

An additional proposal was to retemper the pitch links to reduce hydrogen embrittlement susceptibility. This proposed reprocessing involved removal of vacuum-cadmium plate prior to retempering from HRC 52 to HRC 38. It was unknown whether this reprocessing would produce embrittlement as a by-product of chemical removal of the cadmium or as a result of diffusion of residual cadmium into the steel during the retempering process.

In order to determine if the mechanical properties of the fielded HRC 52 pitch link material was affected by service it was necessary to compare it with virgin material. Similarly, it was necessary to compare the mechanical properties of the fielded HRC 52 pitch link material which was chemically treated for removal of vacuum-cadmium plate and retempered to HRC 38 to virgin ESR 4340 heat treated directly to HRC 38.

The approach to determine the hydrogen embrittlement susceptibility of the fielded HRC 52 and retempered HRC 38 pitch links was to conduct component testing at a much higher torque-load than the service requirement and under arduous hydrogen production conditions. If the pitch links did not fail under these extreme laboratory conditions, then the service life could be reasonably extended.

The objectives of the program were therefore: to evaluate the hydrogen embrittlement susceptibility of the current HRC 52 pitch links in a worst case scenario; to test retempered HRC 38 pitch links for the same susceptibility; and, to compare virgin material to fielded or retempered material to determine any variation in mechanical properties. The program is summarized in the flow chart shown in Figure 3.

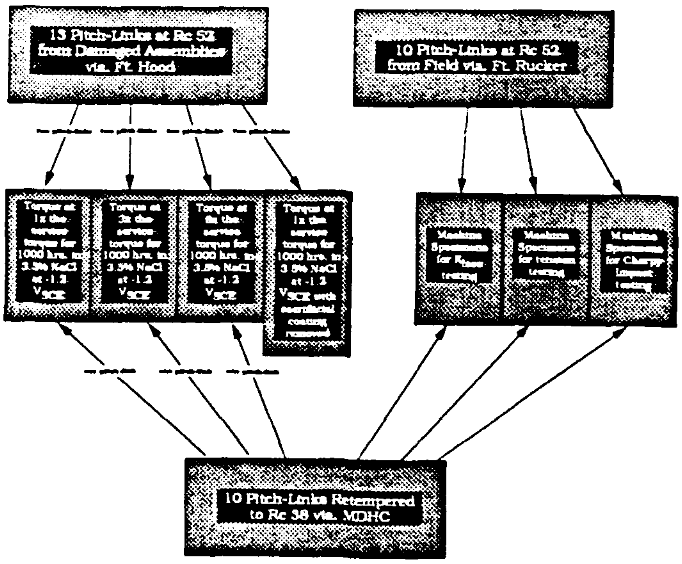


Figure 3. Flowchart detailing the test plan for the evaluation of HRC 52 and HRC 38 pitch links.

EXPERIMENTAL PROCEDURE

Materials

Eight HRC 52 pitch links from AH-64 helicopters at Ft. Hood and three retempered HRC 38 pitch links from the prime contractor, McDonnell-Douglas Helicopter Company (MDHC), were used for torque-load tests. Ten HRC 52 pitch links from the field via Ft. Rucker, seven HRC 38 reprocessed pitch links from MDHC, and virgin 4340 ESR material from MTL were used for mechanical property and hydrogen-induced stress corrosion cracking testing.

Torque-Load Testing

Pitch links were evaluated by a 1000-hour potentiostatic immersion test. The test arrangement is shown in Figure 4. A large plastic tank was used to hold approximately 20 gallons of 3.5% NaCl solution. Two fielded pitch links and one reprocessed to HRC 38 were torqued to the service-specified level of 75 ft-lb, a second set was torqued to three times the specified level, 225 ft-lb, and a third set was torqued to six times the specified level, 450 ft-lb, as indicated in Figure 3. In addition, the protective cadmium coating was removed from two fielded pitch links which were torqued to the service level of 75 ft-lb. The samples were immersed in 3.5% NaCl and maintained at a potential of -1.2 V versus a saturated calomel reference electrode (SCE) by a potentiostatic control system including a PAR 273 potentiostat, an SCE reference electrode, numerous carbon counter electrodes, and the necessary electrical connections. The pitch links were immersed in solution for 1000 hours. After exposure the pitch links torqued to six times the service level were torqued to a higher value in an attempt to induce failure from any existing cracks. After testing magnetic particle inspection was conducted on the threaded portions of the pitch links to determine if hydrogen-induced cracks were present.

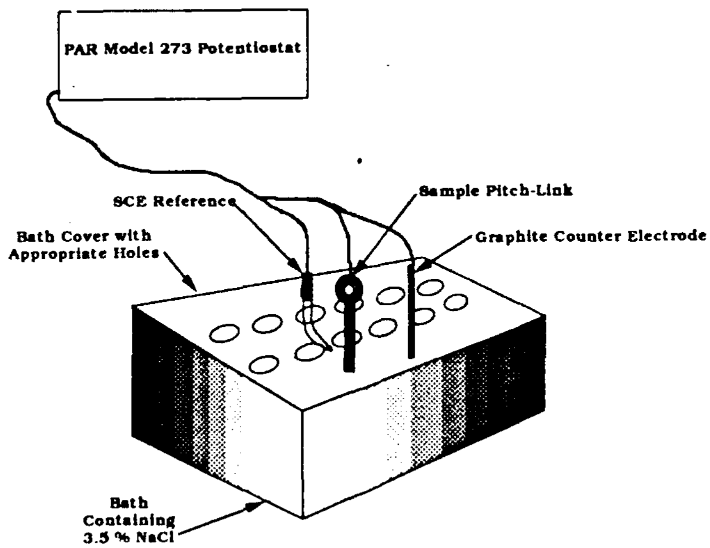


Figure 4. Schematic showing the potentiostatic immersion test setup.

Mechanical Behavior

Standard material property behavior was determined by conducting tensile tests and Charpy impact tests. Specimens were machined from the pitch links heat treated to both HRC 52 and HRC 38 hardness levels (fielded material), as well as virgin 4340 ESR steel heat treated to HRC 52 and HRC 38 harness levels (virgin material).

Hydrogen-Induced Stress Corrosion Testing

The experimental arrangement for testing the hydrogen-induced stress corrosion cracking resistance is shown in Figure 5. This test is an accurate and rapid method to assess the resistance of high strength steels to hydrogen-induced cracking.[1] A standard Charpy sample is step loaded in tension by four-point bending while held at -1.2 $V_{(SCE)}$ in 3.5% NaCl. Crack initiation is judged to occur when the load decreases by 5% within the step period. The load to cause a crack to initiate is used in a linear elastic analysis[1] to determine the plane strain fracture toughness under hydrogen cracking conditions.

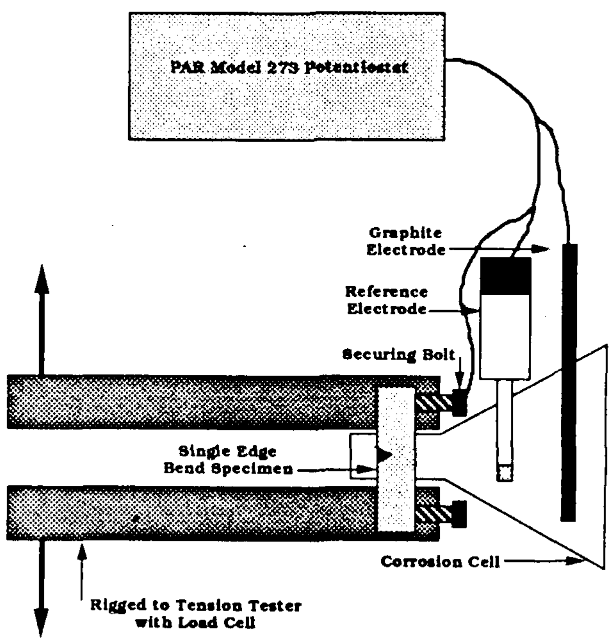


Figure 5. Graphic showing the potentiostatic rising step load bend test.

Fractography

Samples were routinely examined after failure in a scanning electron microscope to detail the fracture surface morphology.

1. TYLER, P. S., LEVY, M., and RAYMOND, L. *Corrosion*, February 1991, p. 82-87.

RESULTS AND DISCUSSION

Torque-Load Component Testing

All samples were intact when removed from the immersion bath after 1000 hours. The pitch links loaded to six times the service torque of 450 ft-lb were torqued to a higher value upon removal in an attempt to induce failure from any existing cracks. In all cases the threads stripped before any evidence of failure could be observed. Subsequent magnetic particle inspection of the pitch link immersion samples did not locate any cracks.

Mechanical Testing

Tensile tests and Charpy impact tests were conducted on specimens machined from HRC 52 pitch links, HRC 38 pitch links, and virgin material heat treated to the same hardness levels. The results of the testing are shown in Tables 1 and 2. Tensile data was consistent for all samples within their respective hardnesses; fielded material did not differ from virgin material.

Table 1. TENSION TEST RESULTS

Specimen 4340 ESR	YS, ksi	UTS, ksi	Elon. %	RA %	Modulus, Mpsi
		<u>Fielded</u>			
HRC 38					
1	170	181	15.5	52.9	27.6
2	168	182	16.8	53.6	33.1
3	166	179	17.0	55.6	27.4
4	166	180	13.6	50.9	28.2
5	158	172	16.0	57.2	27.0
Average	**166**	**179**	**15.8**	**54.0**	**28.7**
HRC 52					
121	210	289	13.2	47.0	27.0
213	209	290	13.6	44.6	26.2
235	208	289	12.4	50.7	26.4
252	214	285	15.5	48.7	25.7
332	209	288	12.5	45.9	28.7
Average	**210**	**288**	**13.4**	**47.4**	**26.8**
		<u>Virgin</u>			
HRC 38					
1VL	173	186	17.0	48.	29.4
2VL	172	180	17.0	48.	28.6
3VL	167	180	20.0	47.	28.3
4VL	168	180	17.0	47.	27.8
5VL	162	173	17.0	48.	28.8
Average	**68**	**180**	**17.6**	**48.**	**28.6**
HRC 52					
1VH	192	300	11	49	30.6
2VH	208	304	13	47	30.6
3VH	Null	Null	Null	Null	Null
4VH	220	312	15	49	31.3
5VH	216	306	13	47	28
Average	**209**	**306**	**13**	**48**	**30.1**

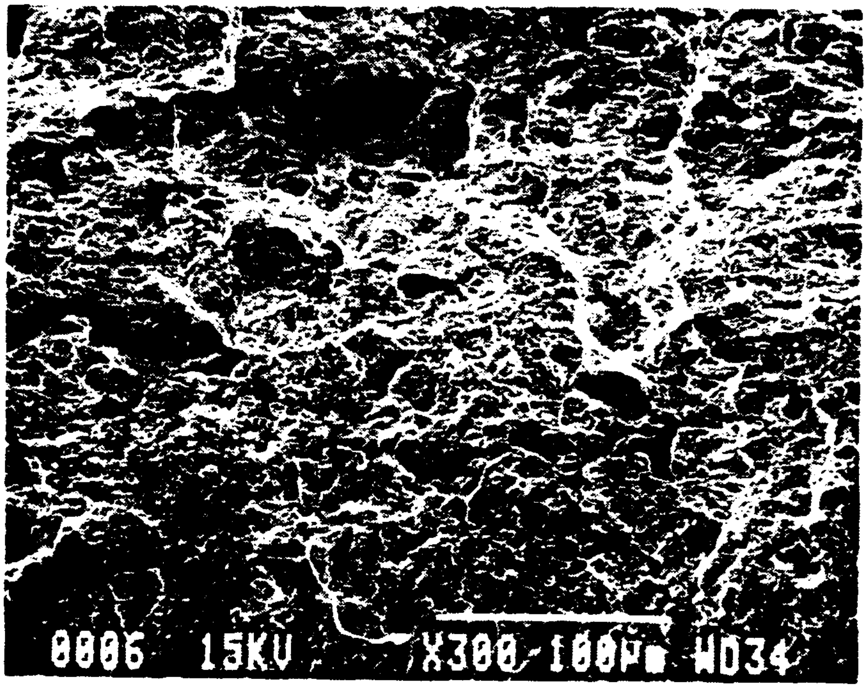
Table 2. CHARPY IMPACT VALUES

Specimen 4340 ESR	Impact (ft-lb)	HRC
	Fielded	
1	35.0	40
2	33.0	41.1
3	42.0	37.7
4	37.7	39.2
5	50.0	38.0
Average	**39.5**	**39.3**
213	28.5	51.9
136	28.5	52.1
Average	**28.5**	**52**
	Virgin	
2L	49.5	38
3L	50.0	38
4L	46.0	38
Average	**48.5**	**38**
7H	25.0	52
8H	26.0	52
9H	25.5	52
Average	**25.5**	**52**

Charpy data for the HRC 38 fielded material showed a lower value of 39.5 ft-lb compared to 48.5 ft-lb for the HRC 38 virgin material, as well as a greater standard deviation, 6.8 ft-lb versus 2.2 ft-lb. Residual cadmium from incomplete chemical stripping may have embrittled the 4340 steel by exposure to high temperatures during the heat treatment process. This would have lead to lower Charpy impact data. An intergranular fracture morphology[2] and the presence of cadmium on the fracture surface would confirm this mechanism. Energy dispersive X-ray spectroscopy was conducted on Charpy specimens 2 and 5 from the fielded pitch links; cadmium was not detected. Fracture surfaces from specimens 2, 5, and 2L were examined for the presence of intergranular cracking; specimen 2L was used for comparison with the virgin material unexposed to cadmium. Figures 6 through 8 indicate a ductile shear process was the mechanism of failure. An intergranular fracture morphology was not observed on the impact samples.

Overall, service exposure does not appear to degrade the mechanical properties of the material tested in this program. Retempering the HRC 52 pitch links to HRC 38 produced the tensile properties expected from ESR 4340 steel heat treated to a hardness of HRC 38.

2. ASAYAMA, Y. *Embrittlement By Liquid and Solid Metals*, M. H. Kamdar, ed., The Metallurgical Society of AIME, 1984, p. 317-331.



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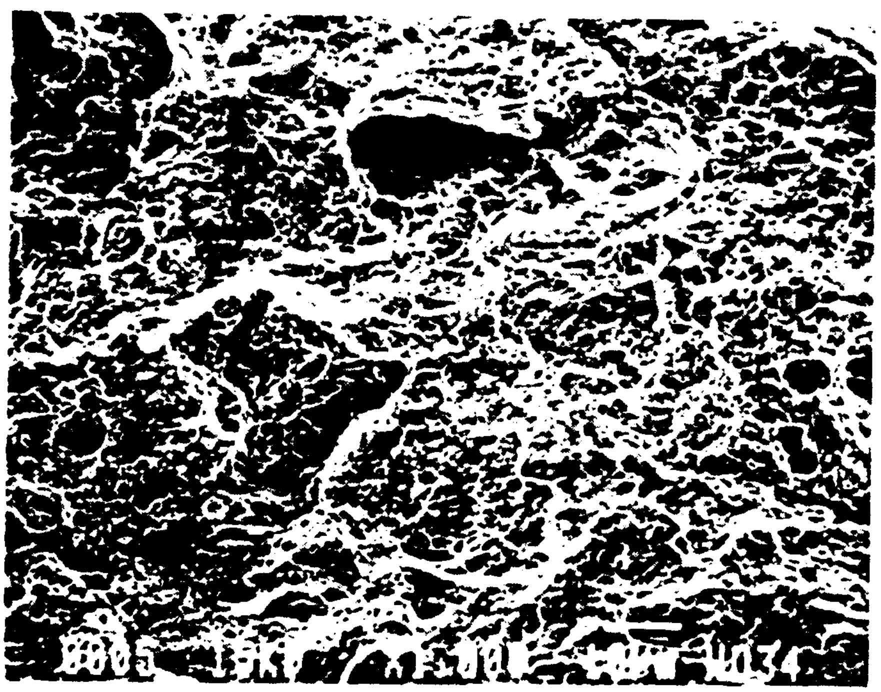
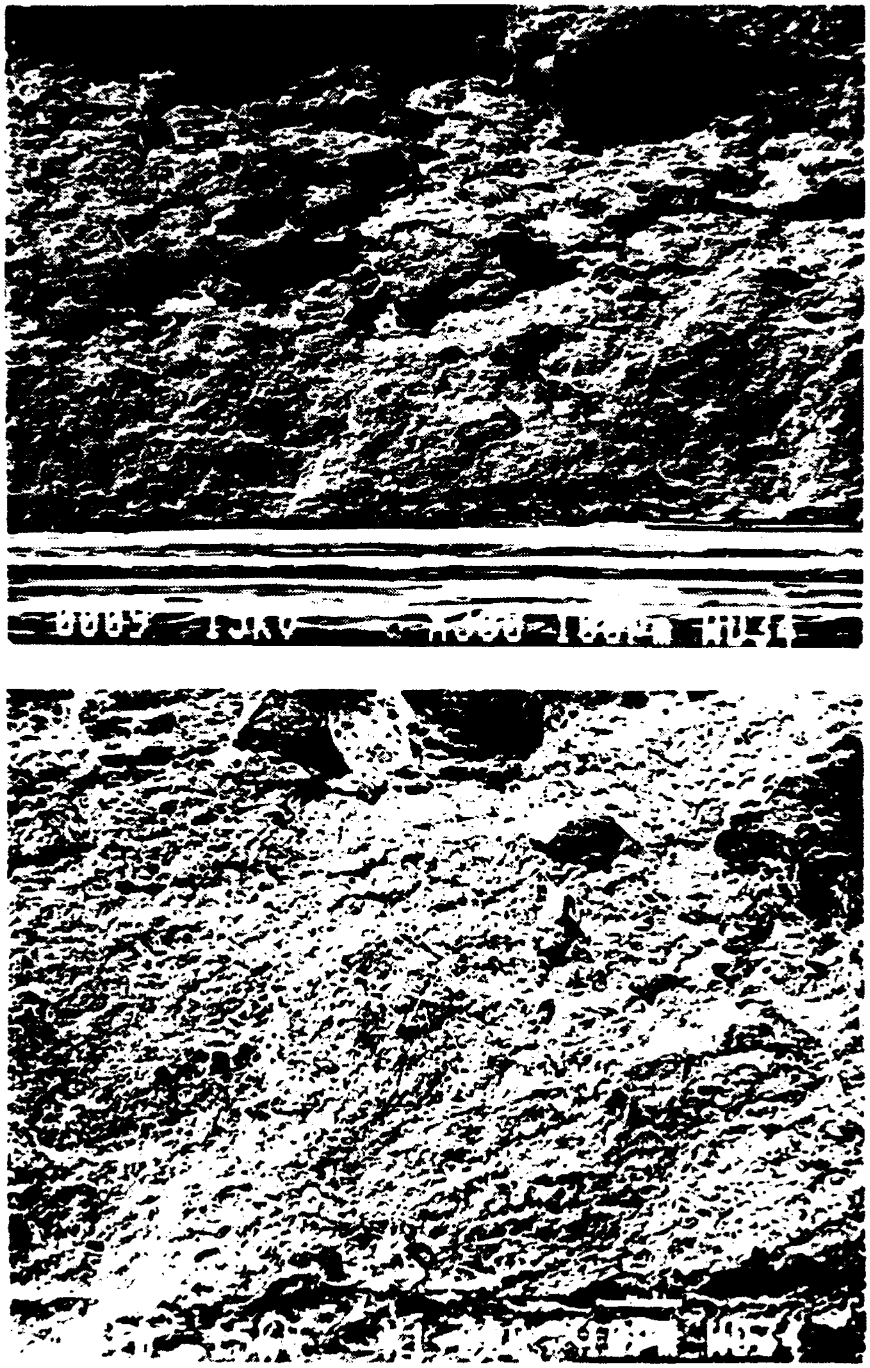


b)

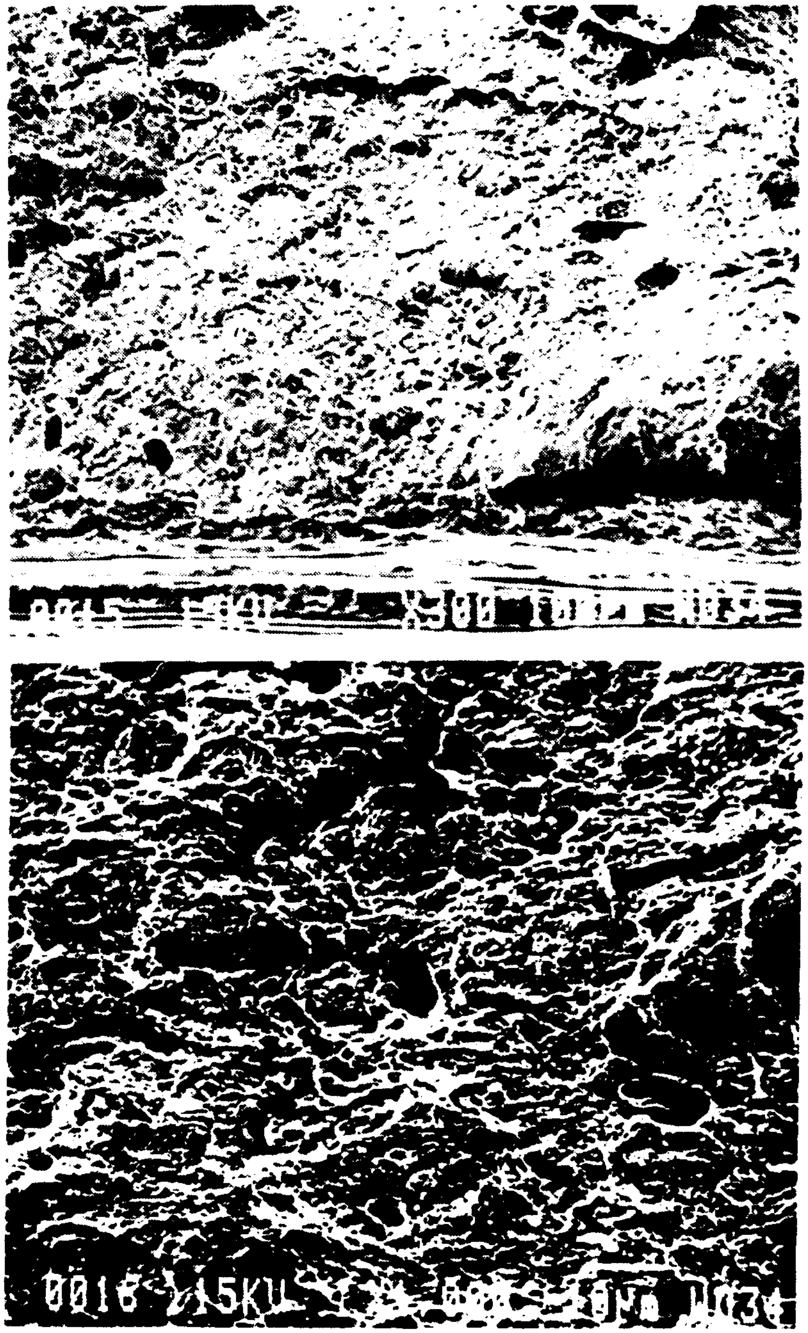
Figure 6. Scanning electron micrographs depicting the fracture surface morphology for Charpy specimen 2 machined from a pitch link retempered to HRC 38. This specimen had the lowest value in its lot, 33.0 ft-lb.



a)

b)

Figure 7. Scanning electron micrographs depicting the fracture surface morphology for Charpy specimen 2L machined from virgin ESR 4340 steel.



a)

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Figure 8. Scanning electron micrographs depicting the fracture surface morphology for Charpy specimen 5 machined from a pitch link retempered to HRC 38. This specimen had the highest value in its lot, 50.0 ft-lb.

Hydrogen-Induced Stress Corrosion Cracking

Hydrogen-induced stress corrosion cracking tests were performed on CV2-type Charpy specimens using a rising-step load bend test as described previously. Samples were tested with and without fatigue precracks grown from the notch. K_{Iscc} data from the tests are shown in Table 3. Values for the specimens from fielded pitch links at HRC 52 were generally higher than virgin material specimens (16.7 ksi$\sqrt{\text{in.}}$ versus 13.5 ksi$\sqrt{\text{in.}}$). Specimens from fielded pitch links at HRC 38 were comparable to the specimens from virgin material at HRC 38 (24.5 ksi$\sqrt{\text{in.}}$ versus 28.8 ksi$\sqrt{\text{in.}}$). These data for hydrogen-induced stress corrosion cracking of the HRC 52 and HRC 38 4340 ESR steels are comparable to data in other reports using the same technique but different heats of ESR 4340.[3,4]

Table 3. STRESS-CORROSION VALUES FROM POTENTIOSTATICALLY-CONTROLLED RINSING STEP LOAD BEND TEST AT -1.2 $V_{(SCE)}$

Specimen 4340 ESR	Impact (ft-lb)	HRC	Fatigue Precrack
	Fielded		
7-2	27	38.0	Y
6-1	19.5	38.3	Y
6-2	27	38	Y
Average	**24.5**	38.1	**Y**
7-1	**44**	**38**	**N**
124	17	52	Y
121	18	52	Y
0062	15.4	52	Y
0136	16	52	Y
0071	17	52	Y
Average	**16.7**	**52**	**Y**
0165	**24**	**52**	**N**
	Virgin		
6L	28.8	38	Y
5L	31.6	38	N
2H	11.4	52	Y
3H	15.8	52	Y
4H	13.1	52	Y
5H	13.6	52	Y
Average	**13.5**	**52**	**Y**
1H	**11.1***	**52**	**Y**

*Tested at -0.6 $V_{(SCE)}$

3. RAYMOND, L. *Effect of Thread Radius, Plating Potential Stress Relief and Crevice Corrosion on the HEM Susceptibility of ESR 4340 Steel Bolts.*, L. Raymond and Associates, Contract DAA629-81-D-0100, Final Report, MTL TR 88-8, April 1988.
4. BUCKLEY, P., PLACZANKIS, B., BROWN, I. G., LOWDER, L., and BROWN, L. *Surface Coatings and Technology*, v. 49, 1991, p. 500-503.

Calculations of the applied stress intensities for the torque values employed in the immersion test were conducted for comparison with the K_{Iscc} values obtained. The following relationship was applied:

$$P = T/(dk) \tag{1}$$

where P is the load, T is the torque applied, d is the diameter (0.875") and k is a factor to take friction characteristics into account, in this case equaling 0.178. The applied stress intensity, K_I, can be calculated from the following relationship:

$$K_I = (P/A)\, F_1\, (\pi\, a)^{0.5} \tag{2}$$

where A is the cross-sectional area, F_1 is a geometric factor of 1.1, and a is the crack length, taken to be 0.7 x thread depth for a 14 thread per inch pattern.

Using Equations 1 and 2, torque levels of 75, 225, and 450 ft-lb produce stress intensities of 3.9, 11.7, and 23.4 ksi$\sqrt{\text{in.}}$, respectively. The pitch links tested in this program were not cracked and should be compared to the nonprecracked data. The nonprecracked specimen made from a fielded pitch link retempered to HRC 38 showed a K_{Iscc} value of 44 ksi$\sqrt{\text{in.}}$ The nonprecracked specimen made from a fielded pitch link at HRC 52 showed a K_{Iscc} value of 24 ksi$\sqrt{\text{in.}}$ Therefore, even at six times the applied service torque the calculated applied stress intensity was less than the K_{Iscc} threshold value for both hardness ranges. This was supported by the absence of failures during the test program.

Overall, the stress corrosion resistance of the materials was characteristic of the microstructure from processing and not characteristic of whether or not the material was fielded. These results confirmed the lack of significant difference between the fielded material and the virgin material.

CONCLUSIONS

1. Service exposure did not degrade mechanical properties of the fielded pitch links made of 4340 ESR steel heat treated to HRC 52.

2. Retempering provided the mechanical properties expected for HRC 38 4340 ESR, as well as greater stress corrosion cracking resistance.

3. Hydrogen embrittlement failure was not induced in HRC 52 and HRC 38 material at torques of up to six times service values.

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AH-64 Apache helicopter pitch links were evaluated for degradation of mechanical properties due to service and susceptibility to hydrogen embrittlement. The pitch links were manufactured from 4340 electroslag remelted steel and heat treated to an HRC 52 hardness level and/or retempered to a HRC 38 hardness level and vacuum cadmium coated. Samples from fielded pitch links and virgin material were evaluated for comparison of mechanical behavior. Static torque-load tests on pitch links immersed in 3.5% NaCl at a potential of -1.2 $V_{(SCE)}$ were conducted for 1000 hours. Stress corrosion cracking resistance under hydrogen embrittlement conditions were determined. Mechanical and stress corrosion testing demonstrated no discernable change in properties due to service. Retempering the HRC 52 pitch links to HRC 38 resulted in properties similar to those expected from the 4340 ESR steel directly heat treated to the same hardness level. The immersion tests indicated no failure of the pitch links even at six times the service torque. The retempered material exhibited greater resistance to hydrogen-induced cracking.

U.S. Army Materials Technology Laboratory
Watertown, Massachusetts 02172-0001
HYDROGEN-INDUCED STRESS CORROSION CRACKING SUSCEPTIBILITY ANALYSIS OF PITCH LINKS FROM THE AH-64 APACHE HELICOPTER-
Paul Buckley, Milton Levy, John Beatty, and Richard Brown

Technical Report MTL TR 92-69, September 1992, 14 pp-
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